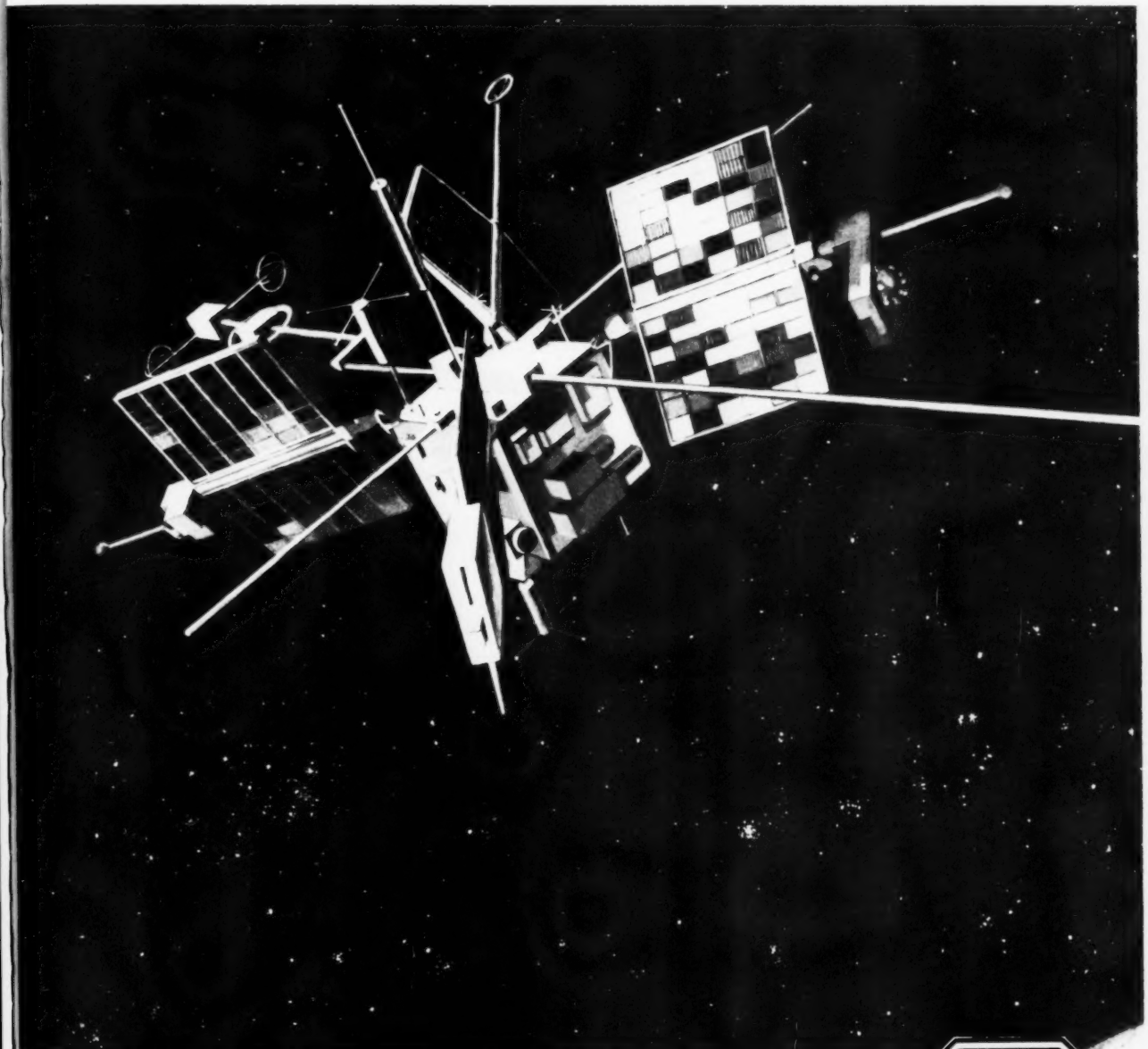
OAR RESEARCH REVIEW

OFFICE OF AEROSPACE RESEARCH ★ UNITED STATES AIR FORCE



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ON THE COVER:

OAR's OV2-5 satellite, launched from Cape Kennedy aboard a Titan III-C rocket on 26 September 1968, carried 12 scientific experiments (including 3 from AFCRL) into a near-synchronous orbit with an apogee of 19,308 nautical miles and a perigee of 18,956 nautical miles. The OV2-5 carries sensors for making particle, geomagnetic, and solar-radiation measurements, and also has two 5-watt (output) S-band telemetry transmitters, each with separate turnstile antennas at the top and bottom of the cube structure. The four 24 x 38-in. solar paddles are attached to the top of the cube by hinges. Power is provided to the spacecraft through solar panels and a nickel-cadmium battery.

OARRP 80-1

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High Resolution with Nondispersive X-ray Spectrometers

DR. DONALD W. AITKEN, Department of Physics and High-Energy Physics Laboratory, Stanford University

Advances in the understanding of atomic and nuclear phenomena have historically kept pace with advances in the development of high-resolution nuclear-radiation detectors. This has never been more apparent than in the extraordinary improvement which we have seen in this decade in X-ray and gamma-ray spectroscopy, following the development in the early 1960's of solid-state silicon and germanium radiation detectors. This chronological linking of scientific knowledge to technological progress can also be viewed in reverse, for the development of improved nuclear-radiation detectors has often closely followed a refinement of our understanding of the interaction of nuclear radiation with matter, or of the sequence of events occurring in the detector material following the primary interaction.

Recognizing these important interrelationships, the Solid State Sciences Division, Directorate of Physical Sciences, AFOSR, has supported* a research effort at Stanford University with the aim of acquiring a better understanding of the processes leading to the detection of X rays in silicon and germanium, as well as in alkali-halide scintillation crystals. Results of this research, as well as of the work of other groups, now enables us to make an interesting and useful comparison of detectors for high-resolution nondispersive X-ray analysis, and to draw some conclusions concerning what to expect in the future.

A very complete and quite technical review of recent developments in X-ray-detection technology, prepared by the author, is soon to be published.(1) The present article is limited to a discussion of resolution in the X-ray energy region. This region spans the energy range from about 1,000 electron volts (i.e., 1 keV) to 100,000 eV (100 keV). This, in turn, corresponds to the wavelength region extending from about 10×10^{-8} cm (i.e., 10 angstroms) down to about 0.1 angstrom. The conversion from energy to wavelength units is easily accomplished with the relation

$$E(\text{keV})\lambda(\text{angstroms}) = 12.396 \cong 12.4 \ .$$

The highest resolution which can presently be attained in X-ray analysis is still realized with dispersive spectrometers. The operation of this type of device is schematically shown in the upper portion of Figure 1. With this type of instrument, the X rays to be analyzed are first collimated, then directed onto a diffraction crystal (either straight or bent), further collimated, and finally transmitted to a detector. The X-ray spectrum is analyzed by stepping the detector and crystal at small-angle increments, or by driving the detector and crystal very slowly and continuously in angle, until the energy region of interest has been spanned. The resulting spectrum is usually recorded either on a strip chart recorder or in a multichannel analyzer used in the multichannel scaling mode.

The physics of crystal diffraction is expressed by the Bragg Law of reflection,

$$n\lambda = 2d\sin\theta \ ,$$

where n represents the order of the reflection, λ represents the X-ray wavelength, d is the spacing between successive crystal symmetry "planes," and θ is the reflection angle of the radiation from the diffraction crystal, as shown in Figure 1.

Two practical disadvantages to the dispersive spectrometer are immediately evident from Figure 1. The first is that it is necessarily a rather large instrument, often requiring it to be placed at some distance from the source of X rays. The second is that the efficiency of the instrument is very low, generally of the order of 10^{-4} to 10^{-5}. This is due to the very small solid angle which is accepted by the Soller collimators, to the very narrow

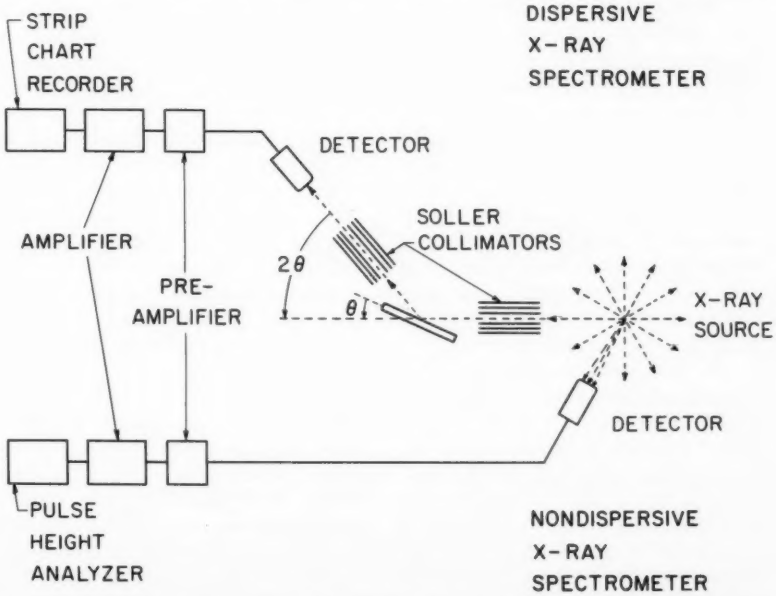

Figure 1. A schematic comparison of dispersive and nondispersive X-ray spectrometers.

*Under AFOSR contract AF49(638) 1499.

energy increment which is reflected at any one position by the diffraction crystal, and to the less-than-unity reflection efficiency of the crystal.

The lower portion of Figure 1 shows schematically a nondispersive X-ray spectrometer. The detector not only records the presence of the X rays, but also records the energy spectrum of the X rays by an electrical output that is proportional to the energy of the X-ray photons.

Several practical advantages of the nondispersive spectrometer are apparent. Among these are that it can be adapted to an experimental configuration with much greater ease than in the dispersive case, and that it features a high total efficiency. The detector element can be chosen to yield practically a 100% absorption and detection efficiency over the energy region of interest, and it can often be placed sufficiently close to the source of X rays (inside the scattering chamber at an accelerator facility, for example) to view a rather significant solid angle. Further, the entire spectrum is being viewed at once by the spectrometer and recorded in the pulse height analyzer, so that much more efficient use is made of the experimental time, or of the lifetime of the source. This is particularly important when one wishes to study weak, short-lived isotopes from nuclear reactions.

The challenge, therefore, is to try and construct nondispersive X-ray spectrometers which still feature very high resolution. Considerable progress has been made in this direction in recent years, utilizing detectors based upon two physical processes: ionization and scintillation. Actually, insofar as the spectral analysis of X rays is concerned, both of these processes require a complete absorption of the incident X-ray photon by one or more ionizing collisions with the atoms within the detector material.

In the ionization detector, the released photoelectron is slowed by subsequent encounters in the crystal lattice in which an equal number of electrons and "holes" are elevated into the conduction band. The presence of an electric field within the detector, created by the application of a voltage across the detector terminals, causes the liberated-charge pairs to flow to the detector terminals, and to be recorded as a small electrical pulse.

Fortunately, the number of charge pairs produced through ionization is very accurately proportional to the energy of the initial photoelectron, and hence to the energy of the incident X ray. This constant of proportionality is expressed by the charge-conversion factor (or the energy-conversion factor) ϵ, expressed in eV per ion pair. Typical values for ϵ are 25 to 30 eV/ion pair in gases, and 3 to 4 eV/ion pair in silicon and germanium. These values depend on several things, including temperature, pressure and impurity concentration.

From this brief discussion one can already deduce the characteristics necessary for the construction of an ionization counter which features high resolution. First, the counter must be of a semiconductor nature, so that an electric field can be sustained within the detector material while still permitting liberated charges to flow through the material to the terminals; yet it should not be so conductive that a large constant leaking current can pass through the detector. And second, the detector must be able to distinguish, with statistical confidence, between closely adjacent energies. This is accomplished, of course, by requiring a statistically significant difference in the number of liberated charges by the two energies. This means that the charge-conversion factor ϵ should be as small as possible. (This oversimplified conclusion is qualified in the following material.)

An important additional feature of ionization counters is their potential for internal-charge multiplication. The application of sufficiently high electric fields to ionization counters can lead to an acceleration of the released electrons to the point where they gain enough energy to have further ionizing collisions on their way to the detector terminal. In this manner the originally liberated charges multiply greatly in number. The presence of a very-low-energy ("soft") X ray, which liberates only a very few charge pairs through primary ionization encounters, can still be detected above the electronic noise level when sufficient charge multiplication has taken place. This multiplication process is again accurately proportional to the initial number of liberated charges, and hence to the incident X-ray energy.

Such internally multiplying counters are called "proportional" or "avalanche" counters, with the terms applied, respectively, to gaseous or to semiconductor detectors. Unfortunately, small nonuniformities in impurity concentrations that are "frozen" into the solid-state ionization counters lead to great variations in the multiplication factor over the geometry of the detector, with a resulting serious broadening of the recorded spectrum. This difficulty, at present, limits the usefulness of solid-state avalanche detectors; however, these devices still hold considerable promise for X-ray analysis.(1) This difficulty is not present in gaseous counters, so that proportional gas counters continue to play a very valuable role in X-ray spectroscopy at the lower energies, particularly in the 100-eV-to-20-keV region.

The scintillation process is neither as direct nor as linearly proportional to the X-ray energy as is the ionization process. In scintillation materials, the ionization collisions lead through successive stages to the ultimate release of a fraction of the energy in the optical region. The initial X-ray absorption is followed, in time, by the emission of a pulse of light which is subsequently recorded by a light-sensitive device, such as a photomultiplier tube or a photosensitive diode. This type of spectrometer is linear to within about 10% for energies below about 100 keV,(2) which still makes it very useful for energy measurements in the X-ray region.

One often defines an "equivalent ϵ" for scintillation spectrometers as the amount of energy which must be deposited in the crystal to produce one electron at the first dynode of the photomultiplier structure. This represents the folded product of the intrinsic efficiency of the scintillation crystal and the quantum efficiency of the photomultiplier tube. A typical value with a NaI(Tl) crystal and a good photomultiplier tube would be about 25 eV per released electron. The resolution attainable with scintillation spectrometers is clearly improved as

this value is reduced. This is accomplished, in part, by seeking new scintillation materials with higher fluorescent efficiencies, as well as by seeking new surface materials for photomultiplier anode and dynode construction which feature, respectively, higher quantum and secondary-emission efficiencies. Considerable progress has been made recently in both directions.(1)

Figure 2 demonstrates relative resolutions which are attainable today with the primary different forms of nondispersive X-ray spectrometers. The resolution is expressed either as the full-width-at-half-maximum of the spectrum in units of energy (eV), or as the ratio, in percent, of this number to the primary photon energy. The remarkable improvement that is being realized with solid-state X-ray detectors is evident in the illustration.

A practical advantage of the high resolution attainable with semiconductor X-ray detectors is illustrated in the sequence shown in Figures 3 and 4. Figure 3 illustrates a spectrum taken by the author and his colleagues in the course of an investigation on the linearity of the fluorescent efficiencies of various alkali-halide scintillation crystals.(2) To deduce the intrinsic efficiency of the crystal, a computer program was devised which smoothed the experimental spectrum, fit it with a polynomial function, and then unfolded the spectrum into its constituent components. This is all shown in Figure 3.

Figure 4, on the other hand, shows the same spectrum as in Figure 3, but as it appears when taken with a silicon detector featuring better than 400-eV resolution. There has been no mathematical manipulation of the spectra shown in Figure 4. One immediately sees that the primary spectrum is not composed of just 4 superimposed monoenergetic spectra, as was assumed when computing Figure 3, but rather of 8 such spectra! The contribution of the Nd^{145} X rays had been assumed to be smaller than it actually is. Although no substantial error was introduced into our particular analysis of Figure 3 by the omission of the 4 Nd^{145} X-ray energies, it is clear that much of the physics of the Sm^{145} isotope might have been lost if

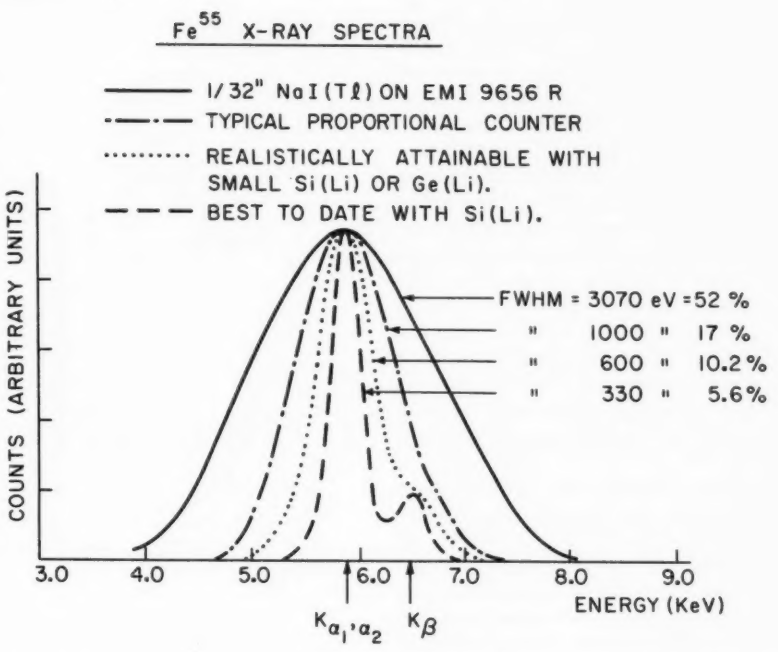

Figure 2. Relative resolutions attainable with three different types of X-ray detectors.

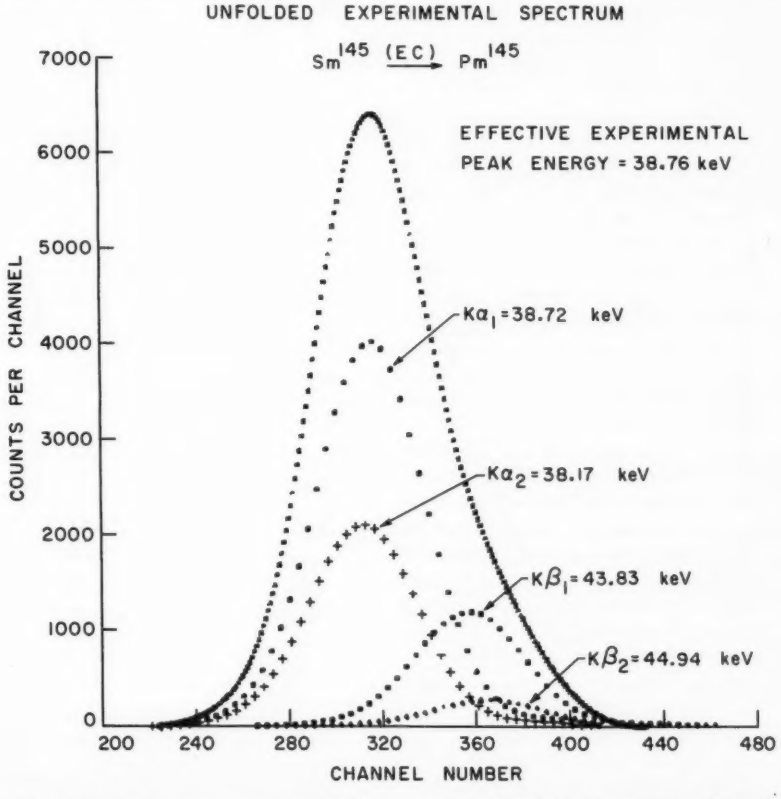

Figure 3. The X-ray spectrum for Sm^{145} obtained with a NaI(Tl) scintillation detector, and unfolded by computer into the assumed components of the observed peak.

one were forced to analyze this isotope solely with a scintillation spectrometer, or even with a proportional counter.

The present practical limits on chemical analysis with very-high-resolution semiconductor X-ray spectrometers are illustrated rather well in Figure 5. Two sets of fluorescent spectra from adjacent elements in the periodic table are shown. The 5 elements spanning from iron to zinc (Z = 26 to Z = 30) are clearly resolved. The limit of resolution is being reached with this particular detector when one tries to separate titanium (Z = 22) from adjacent elements. The detector used for the construction of Figure 5 features about 380-eV resolution at the energies shown.

One of the more remarkable features of Figures 4 and 5 is that this series of spectra was purposely *not* taken with our rather elaborate laboratory system, but instead was taken with the compact commercial X-ray spectrometer shown in Figure 6. The field of high-resolution X-ray spectroscopy with solid-state detectors is, in fact, one in which industry has kept pace with—and at times often led—the laboratories.

One might ask now what further improvement in practical resolution can be expected in the near future. The answer, for the present at least, is given in Figure 7, in which the minimum intrinsic resolution for various types of detectors is presented as a function of X-ray energy.

Although the details behind the construction of Figure 7 are best left to Reference 1, one further aspect of theoretical significance should be brought out here. If the minimum attainable spectral linewidth in ionization counters were determined solely by the number of charge pairs liberated within the detector by the fully absorbed photon or charged particle, then simple statistical considerations show that the full-width-at-half-maximum would be expressed by the relation:

$$\Delta E_{FWHM} = 2.355(\epsilon E)^{1/2}$$

with the charge conversion factor ϵ the same as previously discussed in this paper. But the physical requirement

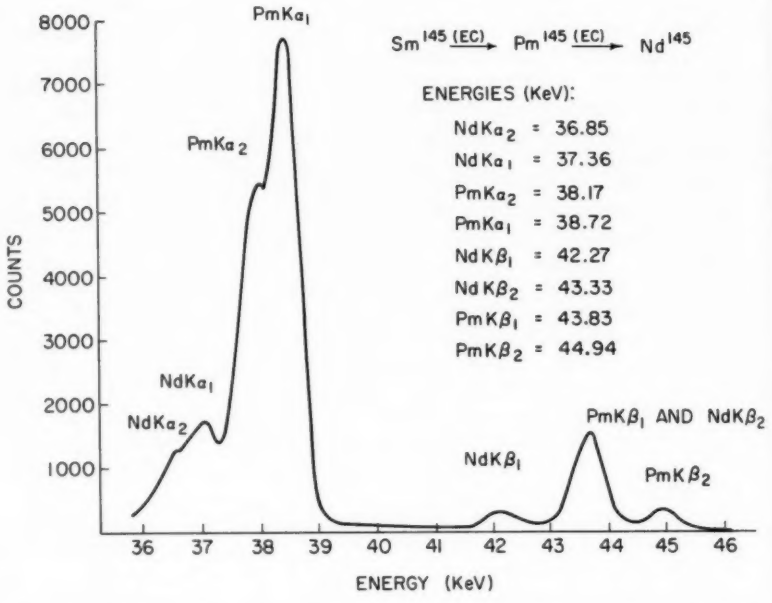

Figure 4. The same spectrum shown in Fig. 3, but obtained with a silicon X-ray spectrometer featuring better than 400-eV resolution. The additional contributions of the X rays from Nd^{145}, neglected in the analysis of Figure 3, appear in this high-resolution observation.

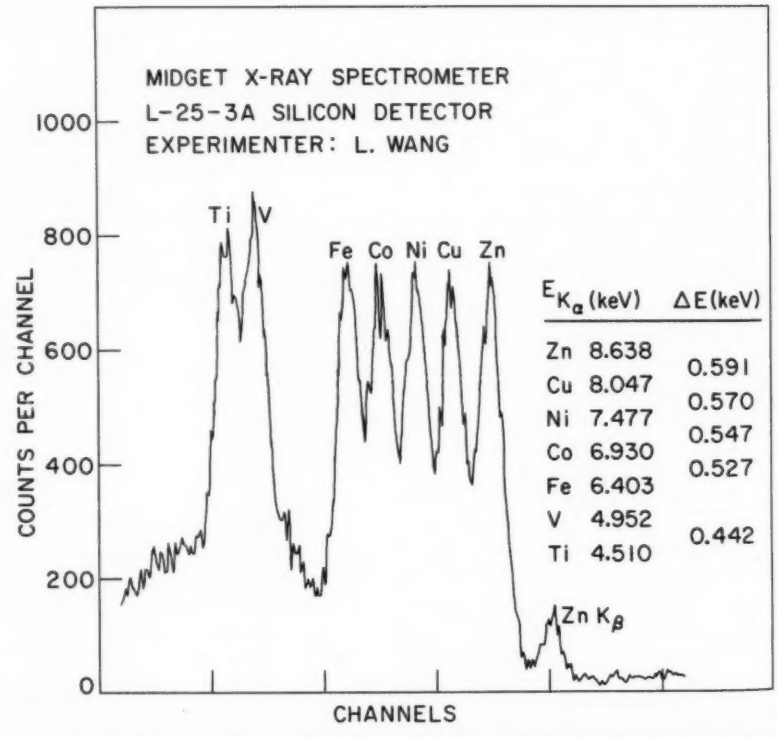

Figure 5. The resolution of fluorescent X rays from two groups of adjacent elements in the periodic table, showing the improvement in resolution as the energy separation becomes greater. The resolution of the system used to take these spectra (see Figure 6) was measured to be about 380 eV.

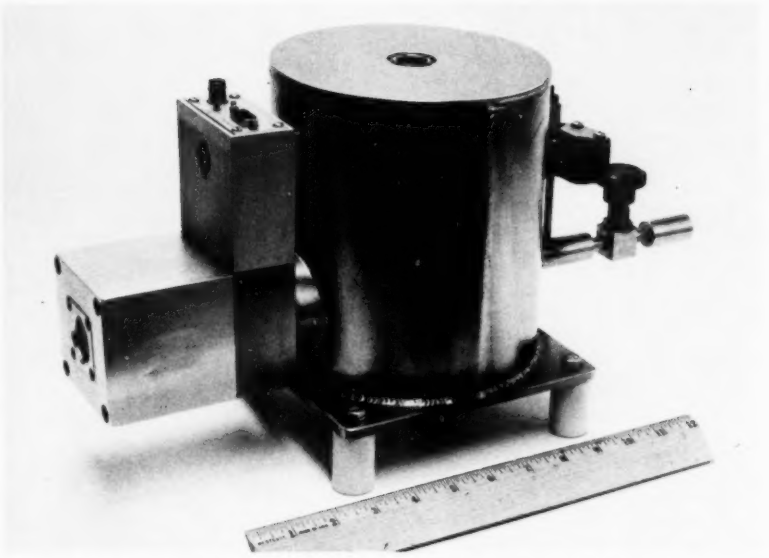

Figure 6. A compact commercial X-ray spectrometer featuring very high resolution. This device was used to take the spectra shown in Figures 4 and 5.

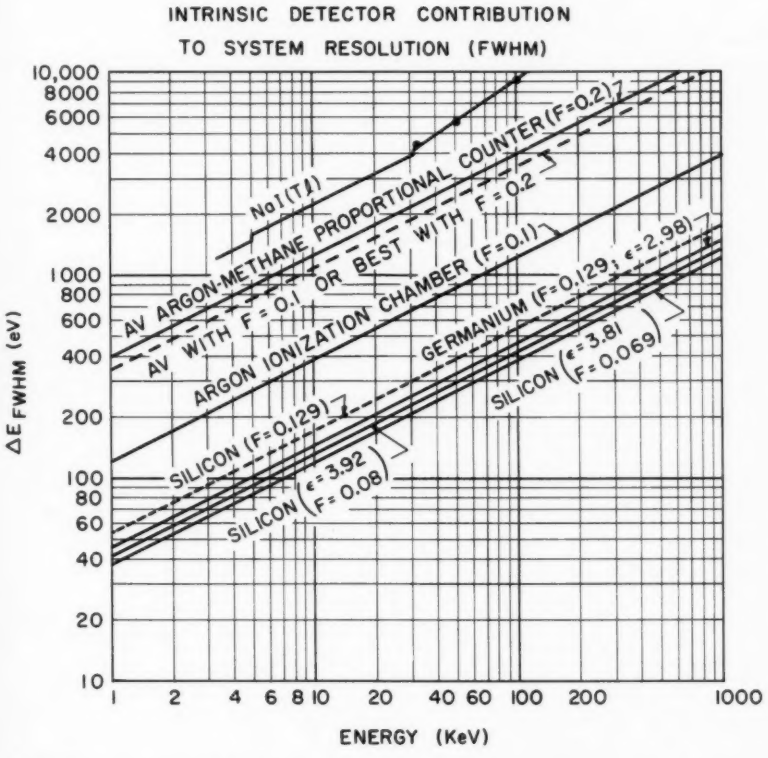

Figure 7. A summary of the best available knowledge to date on the intrinsic contribution of the detector element to the resolution of X-ray spectrometers. Some of these values are qualified in the text.

that the incident photon or charged particle lose neither more nor less than exactly its full energy, when totally absorbed in the active region of the detector, places a firm constraint on the statistical progression of the ionization events. The result of this constraint is that one realizes a significantly *better* resolution (i.e., a narrower spectral linewidth) than one would otherwise expect. This improvement in the resolution is expressed by the less-than-unity value of the Fano factor "F", which multiplies the above expression for the linewidth to yield the correct expression,

$$\Delta E_{FWHM} = 2.355\,(F\epsilon E)^{1/2}$$

One interesting ramification of this result is that the best resolution is *not* necessarily attained with the device featuring the lowest value for ϵ, as was suggested in a previous discussion. The Fano factor for silicon, for example, appears to be about 0.07, whereas for germanium it appears to be about 0.13 (Reference 1). Thus, even though the value of ϵ for germanium is lower than it is for silicon, Figure 7 demonstrates that the highest intrinsic resolution should be attainable with silicon instead of with germanium. The multiple curves shown in Figure 7 result from uncertainties in the precise values for F and ϵ.

This brief review is concluded with words of caution in the interpretation of Figure 7. One cannot summarily cast aside NaI(Tl) in favor of the other kinds of X-ray detectors presented; nor can one cast aside proportional counters in favor of ionization counters, or just reject germanium counters in favor of silicon. Many other factors enter into the decision as to which type of detector should be used for a certain application. Many of these are beyond the scope of the present paper, but can be found in Reference 1. Some of the more practical considerations can be listed here: 1) the very high resolution attained with silicon and germanium detectors are attained only with very small devices (of the order of 25 to 100 mm^2), whereas the resolutions shown for proportional counters can be attained with devices featuring several square meters in area;(1) 2) NaI(Tl) (and other alkali-halide scintillators) can be constructed to thicknesses of many inches, thus providing a very-broad-band response over

a large energy range, without a great reduction in resolution; 3) the very best electronics available today still does not permit the practical attainment of resolutions below about 50 keV with gaseous ionization chambers that are as good as those attained with proportional counters in this energy region; 4) practical resolutions with germanium have been attained that are almost equal to those attained with silicon, whereas germanium offers a higher absorption efficiency and hence a broader energy response (an undesirable feature of the broader energy response of germanium, though, is that it is more responsive to background radiations); and 5) proportional counters with very thin windows are still the only nondispersive detectors that can be practically utilized in the region near or below 1 keV.

One must also be aware that even under the most favorable circumstances the theoretical resolutions shown, at least for the silicon and germanium detectors, cannot be attained at the lower energies (below about 10 keV), owing to spectral line broadening from nonlinearities, in the response of the detector, that are intrinsic to the operation of the detector. These have been the subject of extensive Stanford research.(3-5)

Enormous strides have been made within the current decade in the fabrication and application of nondispersive X-ray spectrometers. Further improvements can be expected in the near future from basic research in the construction of very-low-noise field-effect transistors (FET's); from the analysis of new semiconductor materials; from the possible development of new types of luminous crystals;(1) from the refinement of solid-state theory; and from the refinement of crystal-growing and purification techniques. Exciting advances in physical knowledge should continue to follow improvements in X-ray detection techniques.

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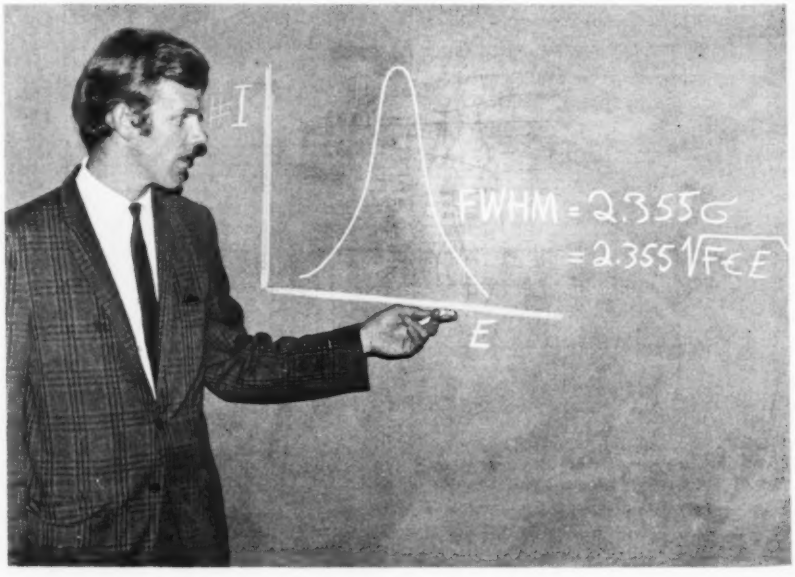

Dr. Donald W. Aitken received an A.B. degree from Dartmouth College in 1958. As the recipient of a National Science Foundation Fellowship, he spent 1959 at the University of Goettingen, Germany, and from 1960 through 1963 at Stanford University. In 1961, while at Stanford, he received his M.S., and in 1963 his Ph.D., both in high-energy Nuclear Physics. He is currently a research physicist at Stanford University involved in research on solid-state X-ray and nuclear-particle detectors for application to astrophysics and nuclear physics.

invertebrate optics

LT COL ROBERT B. KALISCH
Directorate of
Engineering Sciences
AFOSR

Dr. G. D. Bernard and his associates at the Massachusetts Institute of Technology and Yale University School of Medicine are investigating the optics of invertebrate eyes. This interesting research has been supported by AFOSR through the Joint Services Electronics Program. The immediate research objectives are to determine the electrical and optical characteristics of the eyes as well as to develop useful theoretical models.

A variety of invertebrate subjects have been studied, such as tobacco hornworm moths, horseflies, deerflies, houseflies, giant silkworm moths, skippers, and butterflies. Optical and electron microscopy are used for physical measurements and determination of the geometry involved. As one might anticipate, the laboratory techniques for specimen preparation and preservation have been strained to support this research. Some new methods have been developed for specific problems, such as the preservation of colored eye patterns after the death of the specimen.(1)

These studies are intended to gain an understanding of the optics of invertebrates so that signal processing, data transmission, and geometric configuration can be rationalized. (The analytical methodology of these studies may be surprising.) Conventional ray tracing, spectral filtering, and waveguide transmission are typical topics of concern to Bernard and his associates.

THE DIELECTRIC WAVEGUIDE

One analysis characteristic of the investigators' approach made use of the so-called "superposition" compound eye of the tobacco hornworm moth as a specimen. (See Figure 1.) Earlier analyses (2) of this type of compound eye visualized the cornea-cone array acting as a partial spherical lens which would focus an image on the sensory element—the rhabdom. The resultant image was thought to be the result of the superposition of contributions from many cornea-cone pairs. Some further analysis refined this model, but did not treat the propagation of electromagnetic energy

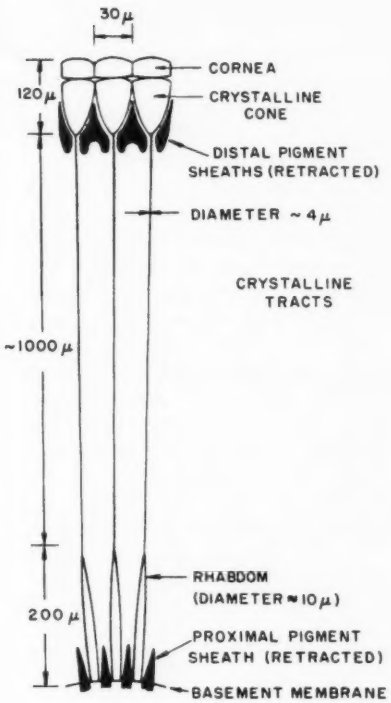

Figure 1. Ommatidia of superposition eye. Dimensions are from studies of the tobacco hornworm moth. ($\mu = 10^{-6}$ m.)

along the crystalline tracts. More recently, it was noted that these crystalline tracts had a higher index of refraction than the surrounding media.(3) This was postulated to be a mechanism for trapping and guiding light. Indeed, this is now the hypothesis being pursued by Dr. Bernard, Dr. W. H. Miller, and J. L. Allen.

The dielectric waveguide for electromagnetic waves is well understood.(4) In this particular application, the 4-micron diameter (approximately 10 wavelengths of visible light) would permit 50 modes of wave propagation. The light apparently propagates down the waveguide and, as it does, becomes distorted. This distortion comes about because the modes propagated travel at different velocities. Hence, the resultant "picture" at the rhabdom would be mixed because, even though the relative mode amplitudes do not change as they propagate down the tract, the relative phases do change; this, in turn, alters the "picture" formed by the summation of modes.

WAVEGUIDE MODE THEORY

The nature of wave propagation as described above, and other supporting evidence, have led Dr. Bernard and Allen to formulate a "waveguide mode theory of the superposition eye." The theory attempts to correlate the established geometry, probable wave-propagation characteristics, and speculation concerning the functional data processing. Essentially, the theory postulates that, although many modes could be excited by the cornea cone, only a few primary modes are strongly excited. These waves are propagated with some loss of phase coherence between modes, but no loss in energy along the crystalline tract. At the rhabdom the energy is combined for all modes to provide a measure of total field intensity. This is the hypothesis for images aligned with the optical axis or within a degree of alignment. In other words, on-axis illumination provides approximately uniform stimuli to all rhabdoms.

Off-axis viewing will excite the rhabdoms nonuniformly. It is hypothesized that the selective excitation of the rhabdoms and comparisons of the neural outputs from the corresponding retinular cells could indicate target motion and give an indication of the magnitude of the movement. This mechanism would not provide information on the direction of motion from a single rhabdom. However, that information is provided by comparisons between neighboring rhabdoms. The important concept developed is that a very small change in the angle of incident light will cause a significant change in the distribution of energy in the rhabdoms and in the neural output of the corresponding retinular cells.

LIGHT ADAPTATION

Another facet of the research being conducted by Bernard and Allen at M.I.T. deals with the light-adaptation mechanism in the eye of the tobacco hornworm moth. It is generally believed that the pigment sheaths shown in Figure 1 serve to accommodate the transmission characteristics of the eye. These sheaths extend when the crystalline tract is transmitting high-intensity waves. Kuiper (5) described this mechanism as the "longitudinal pupil." Recent M.I.T. research in this area has contributed to a better understanding of this "longitudinal-pupil" operation.

The pigment sheaths are lossy and, since the electric field at the boundary of the crystalline tracts is not zero, an energy dissipation will occur. This loss takes the form of a conduction current which heats the granules in the pigment sheaths. The control of these losses is rather sensitive in that the electric field decays exponentially in the sheath. The net result is that extension of the pigment sheath will cause a greater energy loss in transmission down the crystalline tract. Other work has shown the attenuation rate along a pigment-coated tract to be on the order of one tenth of a decibel per micron.(6)

The light-adaptation process attenuates the higher-order modes more severely than the lower-order modes. This occurs as a consequence of the relative magnitudes of the electric field at the boundary of the crystalline tract when a wave is propagating. Higher-order modes have relatively greater fields and so would experience greater losses. Therefore, the information carried by the higher-order modes is lost in the pigment sheath and does not reach the rhabdom.

INTERFERENCE FILTERS

Spectacular light patterns have been observed by Drs. Bernard and Miller in their studies of various types of flies. Many of the Dipteran compound eye corneas seem to be made up of layers which are specialized to serve as optical filters. Striped reflection patterns are seen in some, and irregular pattern shapes are evident in others. One very interesting objective of this research is to attempt to show why these patterns exist.

Probably the most reasonable speculation about these filters is that they are similar to the vertebrate color filters such as retinal oil droplets. Walls (7) has discussed the function of vertebrate filters and suggests that they enhance functional sight. For example, the yellow oil droplets in a pigeon retina tend to eliminate the blue-sky background in the upper field of view, and the red droplets tend to enhance contrasts in the lower field of view against a green-foliage background.

Such correlations are being sought in the research on the eyes of invertebrates. However, knowledge of insect habits is limited and, at present, one can only speculate on these topics.

MOTIVATIONS

Motivations for research of this type are probably as diverse as the investigators. From the viewpoint of AFOSR, however, three specific aims appear dominant. First, of course, there is the need to achieve a better understanding of another part of nature in order to provide a broader base from which to attack specific problems—in other words, to increase our knowledge of the world around us. Second, we need to acquire a knowledge of insect physiology that could lead to improved techniques of insect control. And third, we hope to obtain an understanding of insect vision that could suggest new concepts for detection. Certainly, the sensor size and power requirements for the vision of an insect are intriguing from an applications point of view.

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LASER MINIPULSES

OPTICAL PHYSICS LABORATORY, AFCRL

Ever since spontaneous minipulses were first detected last year in the output of a solid laser, laser physicists have been trying to explain them. Minipulses are incredibly short pulses of light contained within the over-all envelope of the main laser pulse, a pulse which itself is hardly characterized by persistence. A minipulse lasts about a millionth of a millionth (10^{-12}) of a second. This represents a stream of light only about one tenth of a millimeter long, a mere speck of light traveling in space and time. The minipulses occur in evenly spaced sequence, at a rate of more than 100 million a second.

Minipulses in solid media have a number of interesting and puzzling attributes, some annoying to the experimentalist. Their occurrence is unpredictable, as is their exact length and the number in a sequence. A big unresolved question is how spontaneously occurring minipulses in solid lasers are related to the more tractable and slightly longer ones that can be deliberately induced, and to the even longer (10^{-9} second) pulses that, under appropriate experimental conditions, can be routinely produced in the output of gas lasers.

Peter Schweitzer of AFCRL believes that all these short pulses—spontaneous and induced, in solid and gas media, the ultrashort and the merely relatively short—have a common origin. He has also suggested an experiment which might lead to the controlled and predictable production of solid-laser minipulses in the 10^{-12} second range.

To understand how minipulses are generated, we must first know something about the envelope of light emitted by the laser. If we plotted the light intensity of the laser output as a function of time, we would ordinarily see a rather uneven pattern, with the peaks bearing no relationship to one another. But under a condition known as mode-locking, we see that the pulse consists of a regular, periodic oscillation of light intensity.

Now mode-locking is an interesting laser phenomenon in itself, and Schweitzer has done quite a bit of original research on it. Mode-locking, which can occur spontaneously or can be induced by several methods, is the situation that exists when a preponderance of the modes or frequencies (many hundreds in the ruby, for example) comprising the output of a laser become locked into a phase relationship. When this locked phase relationship occurs, there is periodically a confluence of all the upward slopes of the waves, followed by a drifting apart into apparent random and independent behavior, and then a reconfluence. This gives the mode-locked laser output its pulsing quality. The pulsing quality has the effect of breaking the main laser pulse down into many short pulses. If enough modes are locked, with the right phase relationships these short pulses can become very brief indeed.

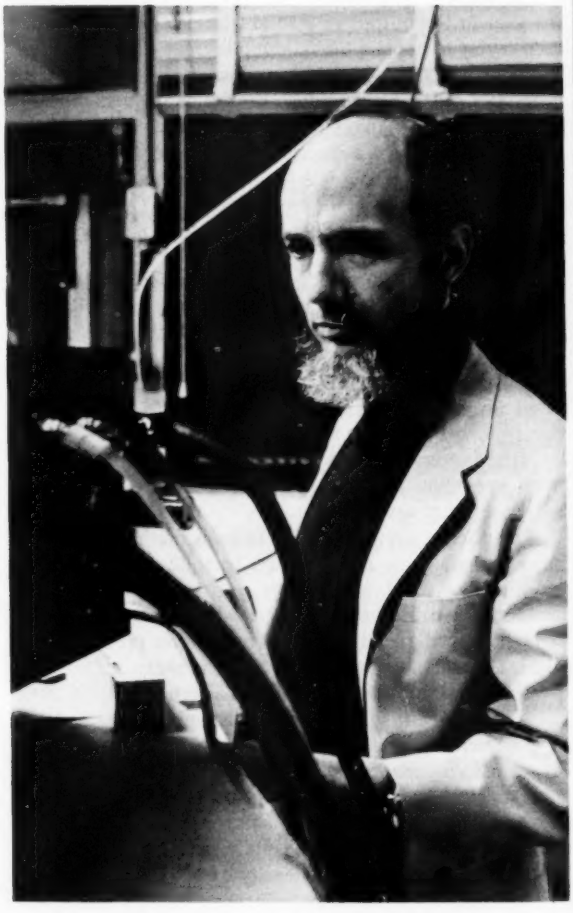
Before we look specifically at what happens in the laser medium to produce minipulses, let's insert a bit of background. The mirrors in a solid-laser cavity between which the light bounces back and forth obviously don't have to be a part of the laser rod. They can be separated by some distance, with the laser medium located in the path between them. This gives experimental flexibility. The experimenter can move a mirror relative to the laser medium to produce a Doppler effect, or he can place light-sensitive dyes in the path between the mirror and laser medium. In general, he can do many clever things and see what happens. It is through such variations of experimental setup that mode-locking is induced.

In Schweitzer's view, further analysis of a particular mechanism (that others have suggested to explain mode-locking in gas lasers) shows that it can account for spontaneous minipulses in solid lasers. Here is Schweitzer's description of the mechanism:

During the instant before the onset of mode-locking, the light intensity from a laser shows marked random fluctuations. In the aftermath of the passage through the laser medium of a particularly high-intensity fluctuation in the over-all laser-pulse envelope, the energy stored in the medium is depleted to slightly below its normal value. Succeeding peaks in the light envelope, with less energy to draw upon, are weakened. By the time the original peak—strengthened after commandeering the energy in the rod—has made its round trip to the mirror and back, the laser medium has not only recovered its lost energy, but has also become energized above its normal value because the weak intervening peaks had not been able to exploit the energy available. So the original peak has extra energy to draw upon on its next passage, and leaves even greater depletion in its wake. This pattern is repeated with each passage. Finally, only the original peak and very-low-intensity light in between remain in the system. The competitively favored pulse then becomes sharper and narrower as its leading edge robs its trailing edge of energy to feed upon.

Schweitzer's description casts some light on the unpredictability and other attributes of spontaneously occurring minipulses. Clearly, the timing of a potentially favorable

peak through the laser medium must be just right or minipulses will not occur. The description also suggests that experimental arrangements in which the light bounces back and forth between two mirrors, with the laser medium in between, are not the most satisfactory for studying minipulses because of the complex pattern of light interference. Schweitzer has proposed an experimental setup whereby the light would travel in one direction along a triangular path formed by three mirrors, with the laser medium placed in one segment. Unidirectional propagation would be brought about by means of a (comparatively very long) "priming pulse" injected onto one of the mirrors from the outside. This scheme may permit the predictable and controlled production of minipulses in solids.



Mr. Peter Schweitzer, shown here with the power supplies used for AFCRL's pulsed ruby-laser apparatus, is a physicist in the Laser Physics Branch, Optical Physics Laboratory, AFCRL, where he is conducting theoretical investigations of the superfluid-like properties of lasers and their implications for laser theory. He is also concerned with "optical antennas" designed to deal with laser light, the coherence properties of which have been disturbed.

Mr. Schweitzer received the A.B. and A.M. degrees in 1951 and 1953, respectively, both in Mathematics and both from Harvard University. In 1959 he completed all course requirements for the Ph.D. in Mathematics at the Massachusetts Institute of Technology. And, in 1966, at Zurich University, he completed all requirements except the thesis for the doctorate in Physics. He has several publications to his credit.

queueing theory applied to time-sharing problems

MAJOR WILLIAM R. TROTT
Directorate of
Mathematical Sciences, AFOSR

"They also serve who only stand and waite. . ." –J. Milton, "On His Blindness."

. . . In particular, the standers and waiters can maximize the over-all performance and profitability of a service facility. Should the reader find himself in a queue in the near future, and be served in the manner described below, he will have sufficient time to ponder the effects of the research program of the Mathematics Division, AFOSR, and perhaps to weigh the advisability of investing in the service facility.

Much traditional queueing theory assumes, and is applied to, service operations that are contiguous in time; i.e., once service for a particular customer is begun, this operation continues until the customer is completely serviced. More recently, and certainly as a result of the expanded application of data-processing systems, the attention of statisticians has been directed to queueing-theory models in which the service operation is not so restricted, i.e., in which the service operation may be interrupted. Such a situation may arise when the customers have varying priorities, and experience different costs per unit time of delay. An important objective in setting up a model for such a facility is to maximize, in some sense, the over-all performance of the facility by minimizing the over-all waiting time. Not surprisingly, the suggestion has been advanced that a data-processing facility might be most efficiently utilized if it were time-shared among several customers, perhaps in this manner.(1)

Under a contract with AFOSR, Dr. A. G. Konheim of the International Business Machines Corporation has examined various aspects of such a model, in particular the determination of an optimum service policy or, if you wish, a queue discipline, for a single-server facility designed to serve m customers. The efficacy of the service policy is measured by the "expected value" of an over-all waiting time for the facility: the weighted sum of the waiting times for each individual customer. In particular, Dr. Konheim has demonstrated that the service policy which minimizes this quantity for the time-sharing problem with m customers can be "composed," so to speak, from the corresponding policy in two-customer problems. The complete details of his solution are to be published in the near future.(2) They are based, in part, on his previous research on a single-server facility designed to serve two customers, undertaken jointly with Drs. D. Chazan and B. Weiss of the same organization. This latter work will also be published in the near future.(3)

The purpose of the present article is to announce these results and roughly outline Dr. Konheim's methods. He begins by defining a processing schedule, i.e., an allocation of facility time to each of m customers, when all require service and as each in turn is "completely serviced." A single remaining customer is served to completion. The determination of an optimum service policy which minimizes the over-all waiting time is, essentially, equivalent to the problem of determining the shortest path, in a certain sense, between two points.

To this end, the processing schedule may be said to determine a path, in this sense, between two points. Next, a family of cost functions is defined which, in turn, allows a certain path integral on the family of paths between these points to be defined. The form of the integral shows that the "shortest path for the r customer problem" can be obtained from the "shortest path for the r-1 customer problem." In turn, an effective computational procedure for constructing the optimum schedule is provided. And, in conclusion, it is shown that a certain shortest path exists and is in fact equal to the "minimal over-all waiting time" for the facility.

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new electrochemical solar cell

SPACE PHYSICS LABORATORY, AFCRL

A new electrochemical cell for the direct conversion of light and other radiant energy into electrical energy has been developed and is being tested at AFCRL. The cell performs roughly the same function as a silicon solar cell, but has potential advantages of cost, low internal resistance, high output voltage, and tolerance to radiation.

The photoregenerative device was developed by I. E. Theodorou and Dr. Richard Payne of AFCRL. It is a simple galvanic cell consisting of nothing more than a silver-chloride anode and a perforated platinum cathode. These two electrodes are sealed in a gas-tight cell containing an aqueous potassium-chloride electrolyte. The cell is roughly the size of a cigarette lighter, 1 cm thick, and

10 cm^2 on a side.

The electrochemical reaction is $Ag + \frac{1}{2} Cl_2 = AgCl$. The photochemical reaction reverses the process: $AgCl \rightarrow Ag + \frac{1}{2} Cl_2$. In the photochemical reaction, the silver remains on the anode while the chlorine diffuses into the electrolyte and eventually crosses to the cathode where it is again available for electrochemical reduction. The cell can deliver current continuously during irradiation, or it can simply store the energy.

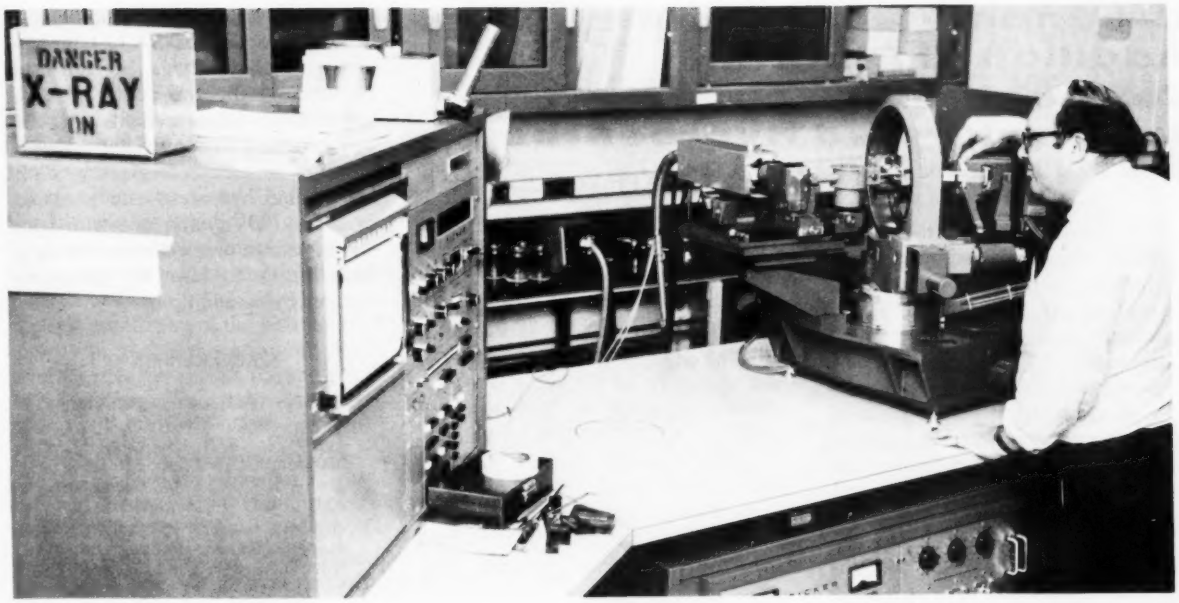
Cell efficiency in visible sunlight at the base of the atmosphere is limited by the sensitivity of the silver chloride to light covering a spectral range of about 4,500 angstroms. The theoretical efficiency is about 6 percent, compared to the 14-percent efficiency of the silicon solar cell; but the cell voltage is higher. When exposed to more energetic radiation than visible sunlight—that is, to ultraviolet radiation in the upper atmosphere—the efficiency is considerably higher.

AFCRL scientists are presently attempting to expand the spectral sensitivity of the silver-chloride electrode.

Mr. Ignatius E. Theodorou (left) and Dr. Richard Payne, shown examining a reference electrode, are research chemists with the Electrochemistry Group, Energetics Branch, Space Physics Laboratory, AFCRL.

Mr. Theodorou received the equivalent of an M.S. in Chemistry from the National University of Greece, Athens, in 1952. He did graduate work at Harvard University in 1953-1954, and joined AFCRL in 1966. He is a member of the American Chemical Society and has three patents and several publications to his credit.

Dr. Payne received the B.Sc. in Chemistry from the Imperial College, University of London, in 1958, the Diploma of Imperial College (D.I.C.) in 1962, and the Ph.D. in Physical Chemistry, also from Imperial College, in 1962. He was an Associate of the Royal College of Science, London (1958), and an Associate of the Royal Institute of Chemistry, London (1957). Dr. Payne came to AFCRL in 1964 from Tyco Laboratories, Inc., Waltham, Mass. He has several publications to his credit.



automation of X-ray-diffraction analysis

SOLID STATE SCIENCES LABORATORY, AFCRL

AFCRL has placed in operation a completely automated system for making X-ray-diffraction measurements of crystals. The system is controlled by an IBM 1800 computer which can be programmed to perform all analytical operations. The computer operates auxiliary equipment for orienting crystals in any arbitrarily preprogrammed position with respect to the X-ray beam. It records data, makes appropriate calculations, and plots the results. The system is an on-line system, and can accept information in either digital or analog form.

The AFCRL automated system is among the pacesetters in a trend toward the increasing use of automated systems for crystal analysis and characterization. Its specifications were set forth by Dr. Harold Posen of AFCRL. The system was built for AFCRL by Picker X-Ray Corporation, White Plains, New York.

X-ray diffraction is one of several kinds of measurements made by crystallographers to determine the structure and properties of a crystal. Although the automated system is presently being used only for X-ray-diffraction analysis, it is capable of handling a variety of conventional analytical processes on a time-splicing basis. Planned as future inputs are such analytical methods as neutron activation, mass spectra, and Mössbauer analysis. Hall-effect measurements, electron-spin resonance, and many other techniques can also be incorporated into the basic system.

Automated crystal analysis has become a clear necessity in solid-state-materials research. Any well-equipped solid-state laboratory with facilities and skills for growing electronically useful materials can produce a sizeable daily output of potentially promising crystals. This daily output could quickly swamp the laboratory's analytic capability. Analysis, however, is an essential feedback to the crystal grower who otherwise must proceed on a trial-and-error basis. The AFCRL automatic X-ray diffractometer can do a more complete, accurate, and versatile job in one unattended 24-hour period than could be done manually in a month.

X-ray-diffraction measurements tell the crystallographer how atoms have arranged themselves in the crystal-lattice network. For a particular crystal, the crystallographer may also want to know the variations in atomic ordering, or the degree of preference an atom has for unlike neighboring atoms. Often, very subtle alterations in the crystal-growing process—temperature, rate of growth, minute increases in dopant materials—can result in gross changes in crystal structure and properties.

Dr. Harold Posen, shown adjusting the diffractometer of AFCRL's automated X-ray-diffraction-measurement system, is a research physicist in the Properties and Phenomena Branch, Solid State Sciences Laboratory, AFCRL. He is currently conducting theoretical and experimental research on the effects of ultrahigh pressures on selected materials over an extremely wide temperature range. He is also working on the application of electronic computers to the automation of research equipment, and is concerned with the development of new programs for data processing and data presentation in the solid-state sciences.

Dr. Posen has a B.S. in Engineering Physics from the University of Toronto (1952), and an M.S. in Geophysics (1956) and a Ph.D. in Metallurgy (1963), both from the Massachusetts Institute of Technology. He holds membership in the American Society for Metals, Sigma Xi, the American Crystallographic Association, and the American Institute of Mining, Metallurgical, and Petroleum Engineers.

Organometallic Chemistry: the Addition of Diboron Tetrachloride to Unsaturated Hydrocarbons

1ST LT RALPH W. RUDOLPH
The Frank J. Seiler
Research Laboratory

A knowledge of the relationship between reaction mechanisms and molecular structure enables the chemist to prepare new compounds possessing desirable properties much more easily than if this knowledge were not available. Thus, as the knowledge of molecular structure and reaction pathways is enlarged, it is natural to expect the tempo of major chemical breakthroughs to increase correspondingly.

A need for new lubricants, coatings, and plastics has arisen with the advent of each of the Air Force's new high-performance aircraft and guided missiles. Advances in chemistry are required to provide these new materials. Thus, it is imperative to learn more about reaction mechanisms and molecular structure in order to keep pace with the rapidly growing need for new and different chemical compounds.

The mechanism by which unsaturated organic molecules react is of special interest, since these compounds are useful polymer precursors. In 1961 Holliday (1) postulated that diboron tetrachloride, B_2Cl_4, adds to unsaturated molecules in such a manner as to give products with a cis-configuration. However, his ideas remained unconfirmed. Recently, an experimental study by 1st Lt R. W. Rudolph (2) of the Chemistry Division, Frank J. Seiler Research Laboratory, showed conclusively that the postulate was correct. The mechanism was shown to be consistent with a four-center transition state which can be termed a "pi-complex" since the pi-bond of the unsaturated species can "donate" to vacant orbitals in B_2Cl_4.

The addition of B_2Cl_4 to HC≡CH was shown to be consistent with the above mechanism by demonstrating that cis-$(Cl_2B)HC{=}CH(BCl_2)$ was the exclusive reaction product. Infrared and Raman spectroscopic investigations showed that the "mutual exclusion rule" (3) was not operative, and that the data were consistent only with the cis-structure.

The reaction of B_2Cl_4 with cis- and trans-2-butene was also shown to be stereospecific and consistent with cis-addition. Experimentally, it was first necessary to convert the addition products to their corresponding diols by alkaline hydrolysis and peroxide oxidation. When compared with samples of known configuration, the diols were shown to have the structures required by cis-addition.

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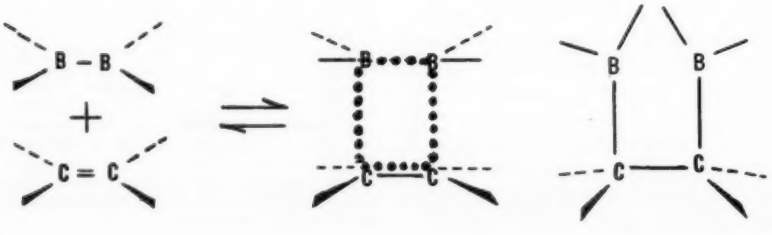
First Lieutenant Ralph W. Rudolph, shown here preparing cold traps in his vacuum system prior to transferring a sample of diboron tetrachloride to a reaction vessel, is a research chemist at FJSRL. He received his B.S. in Chemistry, with high distinction, from Pennsylvania State University in 1962, and was commissioned a second lieutenant in the Air Force Reserve as a distinguished military graduate. To permit him to attend graduate school, the Air Force delayed the start of his active duty.

Lt Rudolph received his M.S. in Chemistry in 1964 and his Ph.D. in Inorganic Chemistry in 1966, both from the University of Michigan. His dissertation was on the preparation, properties, and chemistry of di-fluorophosphine ligands. He was awarded the 1967 Fajan's Prize for the outstanding thesis at the University of Michigan in the past two years. At FJSRL he is on his initial active-duty assignment.



AEROSPACE INSTRUMENTATION LABORATORY, AFCRL

sensitive hygrometer adapted for AWS operational aircraft

A sensitive and accurate instrument for measuring atmospheric humidity has been installed in an Air Weather Service (AWS) C-135 weather-reconnaissance aircraft making monthly observational flights over a flight track extending from California, across the North Pole to Mildenhall, England, and back.

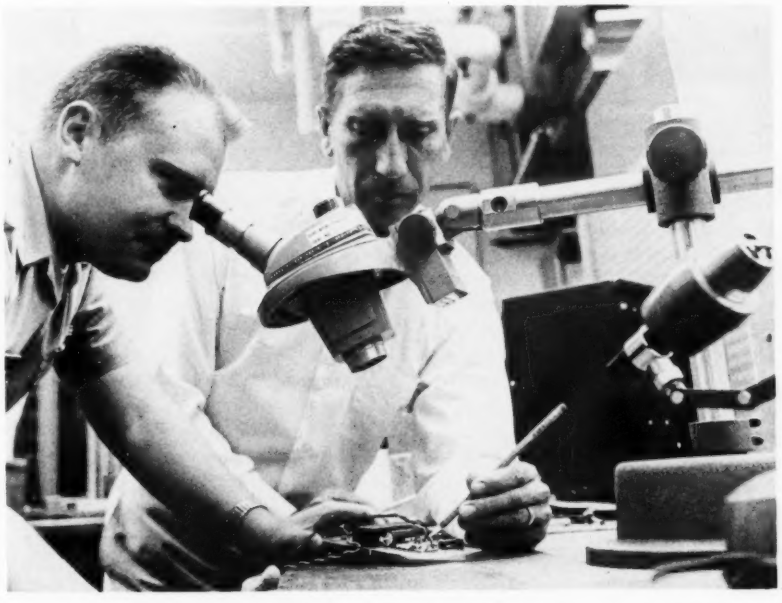
The installation of the instrument, known as the alpha-radiation dew-point hygrometer, marks the end of a development program that began at AFCRL more than 5 years ago. The hygrometer itself was developed under AFCRL contract by Honeywell. The test and experimental program was conducted by AFCRL over a period of several years. During this time, AFCRL has sent the instrument aloft on scores of balloon and U-2 flights to collect upper-atmosphere humidity data.

Knowledge of the moisture content and its variability in the lower stratosphere is a major factor in both weather forecasting and infrared instrumentation. The absorption of infrared solar energy by nonuniformly mixed water vapor can lead to differential heating causing changes in pressure gradients and thus modification of circulation patterns. Unexpected amounts of water vapor in the stratosphere can also affect the performance of a range of Air Force infrared devices, from surveillance instrumentation to horizon seekers in spacecraft.

The AFCRL hygrometer is characterized by its fast reaction time and its sensitivity over a range of temperatures. The instrument consists of a source of alpha particles (polonium 210), a thermoelectric cooler, radiation counters, and a thermistor for measuring temperature changes. The hygrometer works in the following way: A mirrored or polished surface coated with radioactive polonium 210 is cooled by the thermoelectric cooler until frost collects on the polished surface. The frosted surface absorbs some of the radiation emanating from the surface. The alpha-particle count is decreased, and this decrease is read by the particle detector which is separated from the mirror by a 1-millimeter air space. When the decreased alpha radiation is detected, the current flow of the thermoelectric cooler is reversed. This action then causes heating of the mirror and the evaporation of the frost. When the radiation count increases again, the current flow is again reversed, the mirror is cooled, frost accumulates, and the alpha-particle count is decreased. This cyclic process is extremely rapid so that essentially one temperature, at the particular ambient atmosphere being sampled, is maintained. This temperature is the dew-point (or frost-point) temperature—a basic atmospheric moisture measurement.

The instrument aboard the AWS C-135 is rugged and compact, the external portion weighing only 1.6 pounds and measuring 4 x 3 x 3½ inches. Frost points as low as -70 degrees C have been recorded and, in dense clouds, the dew-frost points have approached to within a half degree C of free-air temperature. The hygrometer provides dew-frost points corresponding to relative humidities between 100 and 2 percent from sea level to 40,000 feet altitude.

F. J. Brousaides and Captain D. C. Westhorp of AFCRL are monitoring the equipment on the flights of the C-135 aircraft.



Captain David C. Westhorp (left), an electrical engineer, and Mr. Frederick J. Brousaides, a physical chemist, use a stereo zoom microscope to examine the alpha-radiation dew-point hygrometer. Both men are with the Direct Sensing Techniques Branch, Aerospace Instrumentation Laboratory, AFCRL.

Captain Westhorp received his B.S. in Engineering Sciences from the Air Force Academy in 1962, and his M.S. in Electrical Engineering from the Air Force Institute of Technology in 1964. He is currently studying refractive-index sounding techniques, carrying out a theoretical and laboratory investigation of microwave refractometers. He is a member of the Institute of Electrical and Electronic Engineers.

Mr. Brousaides received his B.A. in Chemistry from Boston University in 1944, and his M.S. in Chemistry from Northeastern University in 1961. In order to improve instrumentation and to anticipate future operational requirements, he is presently evaluating immersion-type sensors used in meteorology. His areas of interest include hygrometry and hypsometry. Mr. Brousaides has several publications to his credit.

BRIGHTNESS OF CHEMILUMINESCENT CLOUDS

When AFCRL scientists first released nitric oxide from a rocket-borne high-pressure reservoir into the upper atmosphere, they were surprised to find that the resultant chemiluminescent glow was much brighter than expected. This led Drs. D. Golomb, F. P. DelGreco, and R. E. Good at AFCRL to investigate this anomaly by simulating the upper-atmosphere release. They found that, when nitric oxide reacts with atomic oxygen, a major constituent of the upper atmosphere, the photoemission rate exceeds by four to five orders of magnitude the expected rate of NO-O reactions. But the reason for this anomaly was still not explained.

Dr. Dan Golomb, a physical chemist in the Spectroscopic Studies Branch, Aeronomy Laboratory, AFCRL, is shown examining a photograph of a nitric-oxide trail released by a sounding rocket. He is currently engaged in formulating and conducting rocket-borne releases of contaminants into the upper atmosphere to study its composition and dynamics, to generate artificial ionospheres, and to simulate missile trails.

Before joining AFCRL in 1962, Dr. Golomb was associated with the Geophysics Corporation of America, where he did research in vacuum ultraviolet spectroscopy and the release of chemicals into the upper atmosphere. He has an M. Sc. in Chemistry (1955) from the Hebrew University, Jerusalem, Israel, and received his Ph. D. from the same University in 1958 after having completed his thesis at the Weizmann Institute of Science, Rehovoth, Israel. He is a member of RESA and has published several research papers.

Recently, Drs. A. Fontijn and D. Rosner of Aerochem Research Laboratories, Inc., Princeton, N.J., presented an hypothesis to explain the anomaly. During the adiabatic expansion of the nitric oxide, the nitric-oxide temperature drops rapidly and the condensation point of the gas is passed. Therefore, part of the gas may form molecular clusters and, possibly, condensed particles. When a molecular cluster collides with an oxygen atom, an excited NO_2 is formed. The excited molecule subsequently radiates light. The formation of excited NO_2 is greatly facilitated in a cluster-atom encounter as compared to the molecule-atom encounter, because momentum is conserved, and the excited NO_2 does not fall apart during the collision. Hence, the higher probability of light emission in the cluster reaction.

To test this hypothesis, AFCRL scientists conducted a series of tests in the Arnold Engineering Development Center's low-density wind tunnel. The wind-tunnel tests consisted of sampling expanding NO jets with a mass spectrometer. Clusters of up to 600 atomic mass units were detected. The fraction of clusters in the jet could be modulated by varying the reservoir pressure and by adding foreign gases to the jet. Subsequent glow measurements revealed that the radiation intensity is directly proportional to the fraction of clusters in the NO jet. These experimental results strongly support the cluster hypothesis of enhanced light emission. In addition, more insight has been gained into the mechanism of molecular collisions in which chemical energy is converted into light energy.

moving Maxwell

CAPTAIN JOHN F. KANTAK
Directorate of Engineering Sciences, AFOSR

Maxwell's electromagnetic theory, the universally accepted description of all macroscopic electromagnetic phenomena, was presented to the scientific community in the 1860's. About 40 years later Poincaré, Lorentz, Einstein, and Minkowski reviewed the theory from the viewpoint of moving configurations. Thus there developed what is commonly called special relativity. Although the theory of special relativity has been known for 50 years or so, its application to problems involving moving media is relatively new. Dr. Charles H. Papas and his group at the California Institute of Technology, under the sponsorship of the Air Force Office of Scientific Research, are recognized pioneers in solving problems where electromagnetic-energy propagation is influenced by the material characteristics and relativistic effects of moving media.

Maxwell's electromagnetic theory is summarized in two differential equations—the famous Maxwell equations, plus two additional equations called the constitutive relations. The Maxwell equations describe the interdependence of the electric and magnetic fields as well as their individual dependence upon the current and charge sources. The constitutive relations provide a mathematical description of the material medium in electromagnetic terminology which includes the constitutive parameters (dielectric constant, permeability, conductivity) of the medium. In any application, the Maxwell equations and the constitutive relations must go hand in hand and, in problems involving moving media or moving boundaries, effects that are peculiar to the relative motions of source, medium, and observer must be considered. These effects are called relativistic effects and are accounted for by the Lorentz transformations which describe how electromagnetic-field and source quantities, as measured in one reference frame, appear to an observer in a moving reference frame. Certain quantities, however, appear the same to all observers regardless of their motion. Such quantities are called invariants. For example, electric and magnetic fields are not invariants, but the total charge is. To see this, consider an electron traveling at constant velocity through a laboratory. For an observer moving along with the electron, the electron appears to have an electric field only. However, for an observer at rest in the laboratory, the moving electron appears to have a magnetic field in addition to the electric field. This becomes intuitively clear if one notes that the moving observer sees the electron as a static charge whereas the observer at rest sees the electron as a moving electron or a current. Applying simple considerations of this sort to the polarization and magnetization of material media, one is led to the conclusion that the constitutive relations of a material medium depend on the relative motion of the observer and the medium (Haus and Penfield [1], Papas [2]). It is through the constitutive relations that information regarding relative motions is fed back into the Maxwell equations and thus taken into account in any calculation.

As an illustration of a moving boundary problem, consider the scattering of radar pulses by an expanding sphere, a phenomenon that occurs when a ground-based radar interrogates an expanding plasma sphere produced by an explosion. If the sphere were not expanding, one could solve the problem by using the results of Mie and Debye where the variables of the Maxwell equations were separable into ordinary differential equations. However, since the radius of sphere is changing with time, the variables are not separable, and a new method has to be introduced to handle the problem.

Dr. Papas (3) and his group attacked the problem of the expanding sphere, and succeeded in obtaining its solution. They recalled that, if an oscillating source of electromagnetic energy moves toward (away from) a receiver, the frequency of the received radiation will be higher (lower) than the frequency of the source. The shift in frequency is the Doppler effect, which is due to the relative motion of source and receiver. In the case of the model chosen by Dr. Papas, one can think of the incident radar wave as producing a continuous distribution of secondary sources over the surface of the sphere (Figure 1). Accordingly, to the receiver, the scattered field appears to be coming from sources on the sphere. Since the sphere is expanding, these sources are moving radially out-

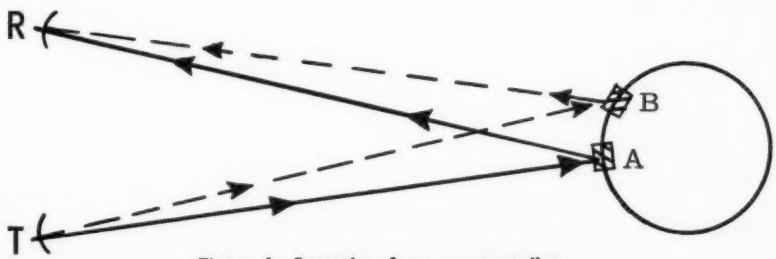


Figure 1.—Scattering from an expanding sphere.

ward with respect to the fixed center of the sphere and, hence, receding from or approaching the receiver at different velocities. In the figure a transmitter (T) illuminates two typical elemental areas (A and B), which scatter some of the incident energy toward the receiver (R). These sources oscillate at different frequencies and, to the receiver, the scattered energy appears as a superposition of waves having different frequencies.

The expanding sphere not only scatters the incident energy but also changes its frequency spectrum. For a high-frequency incident wave, the expression for the frequency of the scattered wave is especially simple:

$$w(\theta) = w_o \left(1 + \frac{2v}{c\text{-}v}\right) \cos\left(\frac{\pi\text{-}\theta}{2}\right),$$

where w_o is the angular frequency of the incident wave, v is the expansion velocity of sphere, c is the vacuum velocity of light, and θ is the angle between the direction of the incident wave and the direction of the scattered wave being observed. For cases where the incident wave has a moderate frequency, the formula becomes complicated, and one has to resort to the data provided in the referenced report.(3) The report also provides data on the change of the radar cross section of the sphere with respect to time.

The solution of the expanding-sphere problem provides an answer to potentially pertinent questions regarding the radar examination of explosions, and exemplifies a practical application of special relativity to a situation where the relativistic effect is due to a moving boundary.

As an example of the part played by the constitutive relations, consider the problem of calculating the electromagnetic reflectivity of an inhomogeneous moving medium, such as a jet stream. Electromagnetic radiation in stationary inhomogeneous media has been treated already by Brekovskikh (4) and many others.(5) However, the problem of electromagnetic radiation in an inhomogeneous moving medium, like that presented by a nonuniform jet stream, had not been treated theoretically prior to the effort of Dr. Papas and his group.

To estimate the capability of a jet stream to scatter incident electromagnetic energy, Dr. Papas calculated the coefficient of reflection of an electromagnetic wave incident at an arbitrary angle upon a plane-stratified slab (the jet stream) whose inhomogeneity was due to the spatial variation of the velocity across the slab.(6) The procedure that was used consisted of determining, by means of the Lorentz transformations, the normal component of the slab's effective wave vector in the reference frame of the laboratory. Then, using the method of invariant imbedding (7,8), the index of refraction was calculated in terms of that component. The advantage of this procedure is that it leads to a solvable differential equation without requiring a knowledge of the wave functions within the inhomogenous medium.

Dr. Papas noted that the spatial variation of velocity across the jet stream causes an apparent alteration of material density which results in a variable dielectric constant. Therefore, the jet stream, by virtue of its motion, would appear to a fixed radar as having electromagnetic properties different from those of the surrounding quiet air, and would reflect incident radar energy. In fact, a fixed radar observer would find that the energy reflected from the jet stream depends on the velocity of the stream, the angle the incident energy makes with the stream boundary, and any material differences between the stream and the surrounding medium. Dr. Papas determined that, if a bistatic radar system is used, the amplitude of the detected signal would be an order of magnitude greater than that obtainable with a monostatic system (Figure 2). This is due to minimum reflectivity at a normal angle of incidence, and increasing reflectivity as the incidence angle becomes more and more oblique. He also noted that reflection from a jet stream is nonreciprocal because, qualitatively speaking, the velocity of the stream makes it appear as an anisotropic medium.

The problems presented here to illustrate the AFOSR-sponsored research of Dr. Papas are indicative of

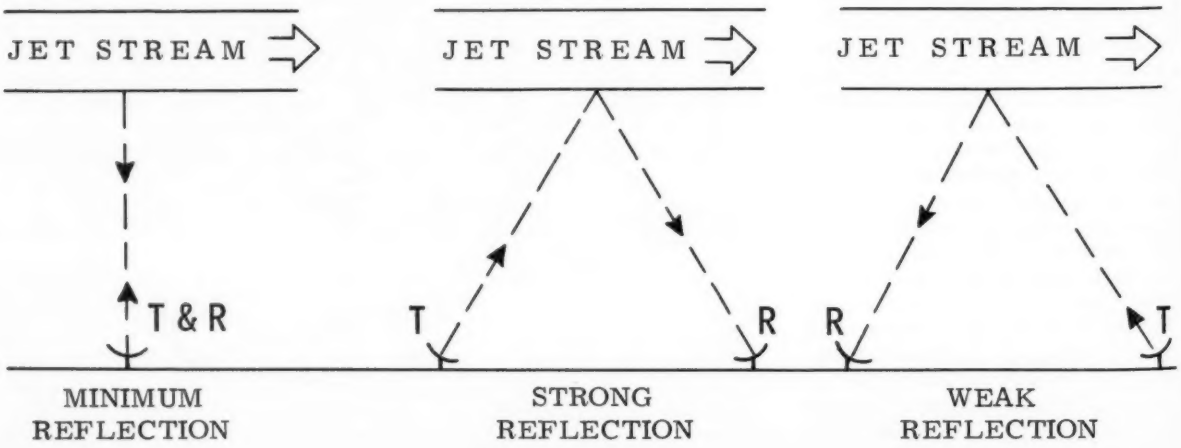


Figure 2.—Jet stream reflectivity.

the type of relativity effects that occur in theoretical electromagnetic-propagation analyses. Our growing laser technology has provided coherent electromagnetic energy for very accurate relativity experiments; but it has also introduced problems involving relativity considerations and the laser–in radar, airborne intercept control, interplanetary communications, and satellite communication and control. These situations will require an accurate analysis of the interaction of electromagnetic energy and moving media.

A problem much closer in time, yet of significance to aerospace operations, is the detection of clear air turbulence (CAT). The invisible CAT can rapidly alter the altitude of any aircraft, and its detection is therefore a primary operational objective. Dr. Papas is attempting to formulate a meaningful model of CAT so that he can define the optimum electromagnetic scattering expressions. This AFOSR-sponsored research is an excellent example of good fundamental work that comes close to the practical world, and is germane to the mission of the United States Air Force.

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This geometric pattern is a portion of AFCRL's 150–foot radio telescope at the Sagamore Hill Radio Observatory in Hamilton, Mass. This hugh dish, in operation since 1962, is used for a variety of measurements, particularly of ionospheric turbulences which cause fluctuations, or scintillations, in radio signals.